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ELECTROSTATIC SPARK IGNITION-SOURCE HAZARD IN AIRPLANE CRASHES

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SUMMARY

The hazard of igniting airplane crash fires by electrostatic sparks, generated when detached airplane parts fly through clouds of dust and fuel mist, was investigated. Within the limits of variables studied, the rates with which airplane wreckage collected a charge were directly proportional to the rate that clay dust or fuel mist was intercepted. Maximum rates of experimental electrification were used to relate energy accumulation to wreckage sizes and trajectories and to estimate minimum hazardous wreckage sizes and trajectories. Comparison of sizes and trajectories of wreckage shown in motion pictures of airplane crashes with these estimated sizes and trajectories indicated that the hazard is small. Of the remedial measures considered, polyethylene coatings were found to offer promise of protection against electrostatic spark ignition.

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INTRODUCTION

During the investigation of full-scale airplane crash fires described in reference 1, an ignition occurred that could not be explained satisfactorily by any mechanism other than by an electrostatic spark. Fire started in a cloud of fuel mist 60 feet behind the stopping airplane when a severed landing gear approached the ground after tumbling through dust clouds, as shown in figure 1. Investigation of the ground impact area and the landing gear led to the conclusion that neither mechanical friction sparks nor Diesel compression of the oleo-pneumatic strut furnished the ignition energy. Accordingly, an investigation was conducted to evaluate the hazard of electrostatic spark ignition in airplane crash fires and to study remedial measures.

It is well established by the literature of electrostatic charging and ignition (summarized in refs. 2 to 8) that spark ignition charges may be accumulated by the collision of solid or liquid airborne particles on insulated objects of sufficient electric capacitance. However, the available quantitative data are inadequate to evaluate the hazard imposed by the materials and conditions involved in airplane crashes. Thus, it was necessary to measure the rates at which airplane parts are charged by impinging clouds of charge carrier (dust and fuel mist). These measurements were made by blowing dust and fuel at full-scale airplane parts of known capacitance and measuring the rates of voltage increase. The controlled variables affecting the charging mechanisms in these tests were charge carrier and wreckage materials and the relative velocities between the two.

Methods of reducing electrostatic fire hazards in industry are well described in references 2, 3, and 9, but they appear to have no direct application to the prevention of airplane crash fires ignited in this manner. The following two remedial approaches have been studied: (1) limitation of energy generation by a noncharging coating and (2) modification of the discharge to avoid ignition. Noncharging coatings were 2812
shown in reference 10 to present impractical maintenance problems, and a search for such a noncharging coating that would meet all the requirements of normal and crash applications was abandoned. An insulating coating used to modify the discharge to a rate too low for ignition, or to quench the ignition, appeared more promising and has been tested. The investigation reported herein was conducted during 1952 at the NACA Lewis laboratory.

APPARATUS AND PROCEDURE

In order to determine the rates with which detached wreckage could be electrostatically charged, landing-gear parts were exposed to an air stream containing electrostatic charge carriers (dust and fuel mist) while motion-picture records were made of the time and the voltage of the charges generated. Figure 2 is a general view of the experimental equipment. Clay dust or fuel mist, or both, dispensed in the $2\frac{1}{2}$-foot diameter blower nozzle, were blown at the suspended, insulated landing-gear parts 15 feet away. Charge-carrying dust or fuel-mist particles impinging on the airplane parts deposited or removed electric charges. The resulting potential was recorded as a function of time by motion pictures of the electrostatic voltmeter deflections. A more detailed description of the equipment is presented in the following paragraphs.

Landing-gear parts. - The major part of an airplane landing gear severed in an experimental crash was rigidly suspended as shown in figure 2. Each supporting wire rope was attached to the landing gear by two series-connected porcelain insulators. The measured capacitance of this insulated landing gear, the voltmeter, and the lead was 200×10^{-12} farad; and the resistance to ground was of the order of 10^{12} ohms. In some experiments the wheel was rotated at about 300 rpm, equivalent to take-off speed, by a removable electrically driven friction wheel. The landing gear was discharged to ground after it had been accelerated to 300 rpm and before the charging experiment was begun.

An alternate method of suspending the wheel without the strut is shown in figure 3; the metal hub and axle were encased in rubber when the charging characteristics of rubber surfaces were determined. The capacitance of this configuration was about 100×10^{-12} farad.

Charge-carrying materials. - The charge-carrying materials that form clouds through which airplane parts may fly in a crash are mainly fuel mist, sand, clay dust, and snow. The term "charge carrier" will be used in this report to refer to finely divided solids and liquids that deposit or remove electrostatic charges on or from flying airplane parts. Although snow was noted to be an effective charge carrier when blown at the insulated landing gear, quantitative tests were limited to the use of JP-3 turbojet fuel mist and dried, pulverized clay soil from the crash site. This clay dust contained 1.5-percent moisture by weight.

Dust dispenser. - The clay-dust charge carrier was introduced into the blower air stream through a pivoting chute from the outlet of the vibratory powder feed bin shown in figure 2. Since the flow rate was unstable, two flow-rate samples were taken as a part of each electrification operation by shifting the chute to a sample container for timed intervals before and after each experiment.

Fuel-mist feed. - The JP-3 hydrocarbon fuel charge carrier was introduced into the blower air stream as a fine mist. This fuel was sprayed through 10.5-gallon-per-hour hollow-cone atomizing nozzles at pressures from 115 to 200 pounds per square inch.

Air blower. - The blower could be regulated to produce the desired airspeeds of 45 and 65 miles per hour as measured at the suspended landing-gear parts 15 feet away. In these crashes an airspeed of 45 miles per hour approximates the translational speed of the landing-gear parts through the air after separation from the airplane. Charge-carrier concentrations in the blower stream were calculated from the mass of charge carrier and the volume of air that were mixed at the blower nozzle.

Potential and time measurements. - The potentials of the insulated landing-gear parts were measured with an electrostatic voltmeter. Since the range of this voltmeter was only 20 kilovolts, sphere gaps spaced to spark at 30 kilovolts were added in an attempt to extend the range of the voltage measurements. The voltmeter and sphere gaps were mounted to form a unit with a timer. A grounding switch and a start indicator were linked to operate when fuel was sprayed or when the dust-dispenser chute was shifted to the blower stream. Voltage, time, and start data were recorded by a 35-millimeter, 8-frame-per-second motion-picture camera. The inertia lag in meter response, although appreciable, did not affect measurements of rates of voltage increase, since only linear portions of potential-time graphs were used to determine these rates.

Ignition-capability equipment. - Studies of ignition capability of discharges from suspended wreckage were conducted with a flowing propane-air mixture. (This gas has a minimum ignition energy very close to that of gasoline hydrocarbons.) Propane and air were metered through orifices of suitable size at pressures regulated to obtain the most easily ignited mixture. This mixture was piped through a flame trap to the nozzle shown in figure 4, which contained a centrally mounted discharge electrode. Sparks between this electrode and charged bodies were thus surrounded by the flowing, combustible mixture.

Protective-coating study equipment. - The apparatus shown in figure 5 was used to determine the ignition capabilities of discharges drawn from the sphere at points of measured coating thickness. The electrometer and coated sphere were charged by connecting the power supply to the uncoated mounting rod for as long as 30 seconds. The power supply was then disconnected and the grounded electrode, either a 1/4-inch-diameter pointed rod or a 2.46-inch-diameter sphere, was brought towards the charged sphere until a spark occurred or until it touched the coating. In order to measure the ignition capabilities of the discharges, a jet of propane-air mixture, prepared as described previously, was directed at the spark gap at 70 to 90 milliliters per second.

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RESULTS AND DISCUSSION

The first data presented are experimental charging rates of landing-gear parts in an air stream containing clay dust and fuel mist. These data are then used to obtain an estimate of the electric energy that could be accumulated by the wreckage flying through dust or fuel-mist clouds under conditions similar to the crashes studied in reference 1. Such an estimate gives an indication of whether the particular landing-gear ignition incident was the result of a borderline ignition energy. Minimum sizes and trajectories of wreckage that may constitute an electrostatic ignition source in an airplane crash are also estimated from these charging-rate data. A count of wreckage that appears to approximate these size and trajectory requirements in the motion pictures of 21 crashes is offered as additional data by which these estimates and the electrostatic ignition hazard may be judged. A study of protective coatings and the selection and evaluation of one example are presented later to indicate the possibility of inhibiting ignition-spark discharges.

Experimental Charging of Airplane Parts

Determination of charging rates. - The maximum rates of potential rise were obtained by plotting potential as a function of time as recorded by motion pictures in each charging experiment. The charging-rate curves obtained did not all rise at zero time when the wreckage and meter were disconnected from ground potential and permitted to accumulate a charge; some curves also showed discontinuities in the rates of potential increase.

These charging-rate lags and interruptions were the result of fluctuations in dust flow due to difficulties with the dust dispensing equipment and the result of fluctuations in the air stream due to variations in wind speed, direction, and turbulence. However, the steepest linear slope of a curve, lasting for a significant potential increase, was measured and represented the maximum potential increase rate for that experiment.

2812 <u>Charging rate as function of dust rate</u>. - The results of a series of experiments in which clay dust was used as a charge carrier are summarized in figure 6. A group of curves, similar to those previously described, were obtained from experiments in which dust was blown at 45 miles per hour and were analyzed to determine the maximum charging rates produced at varying rates of dust dispensing. Charging rates are plotted as a function of average dust flow. Each short horizontal line represents an individual experiment, and the dust rates are plotted as short lines rather than as points in order to demonstrate the probable range of dispensing rate for each experiment. The slope of the line faired through these plotted data indicates that, within the range of variables studied, the potential generated is directly proportional to the amount of dust blown at the landing gear, and that the potential of the landing gear and voltmeter were raised an average of 6 volts per gram of dust blown in this particular group of experiments.

In a crash accident, this result infers that the energy collected by flying wreckage is roughtly proportional to the concentration of charge carrier in the air and the volume of the path swept by the wreckage (with the assumption of a constant charge-carrier particle-size range).

<u>Effect of other variables on charging rate</u>. - In addition to the effect of charge-carrier mass, several other crash-accident variables were studied. Charge-carrier material (dust and fuel), wheel rotation, relative velocity between charge carrier and wreckage, and wreckage materials were varied to determine their effects on the order of magnitude of electrostatic charge accumulation. The conditions and results of pertinent groups of experiments are presented in table I. The maximum rates of potential increase, the concentration of charge carrier in the blower air stream producing each maximum rate, and the maximum rates of potential increase that might be expected at a charge-carrier concentration of 1 gram per cubic foot of air are tabulated in the last three columns. For purposes of comparison, the charging rates of individual experiments were converted to a common basis of 1 gram of charge carrier per cubic foot of air. This conversion is permitted by the linear relation between charging rate and charge-carrier concentration shown in the previous section.

In the succeeding discussion, all charging rates discussed have been converted to the rate expected at an arbitrary charge-carrier concentration of 1 gram per cubic foot of air, unless stated otherwise.

Over the limited range of the independent variables studied, a tenfold range in the magnitude of maximum charging rates resulted from changing the charge carrier and wreckage materials and the impact velocities. A significant but inestimable part of this charging-rate range of 3.9 to 38 kilovolts per second may fall within the effects of day-to-day uncontrolled variables and experimental error. One variable, the charge-carrier material (clay dust against fuel mist), affects more than the magnitude of the charging rate; opposite polarity charges were generated on airplane wreckage materials by clay and fuel impact (see table I). Clay dust consistently charged wreckage positively (+5.1 to +13.3 kv/sec max.), and fuel mist charged wreckage negatively (-3.9 to -38 kv/sec). Charging-rate experiments in which dust and fuel were blown together at the insulated landing gear produced either insignificant potentials or slow potential increases (0.54 kv/sec max., charge-carrier concentration undetermined). This opposite effect of dust and fuel permits the inference that maximum crash electrification will occur only in charge-carrier clouds composed of particles all of which produce charges of like sign, that is, dust alone, fuel alone, or perhaps fuel and snow (refs. 7 and 10 state that snow generally charges aircraft negatively). The contamination of otherwise clean wreckage by fuel or dust did not alter the polarity of the charges or the apparent charging mechanisms of either charge carrier. 2812

Rotation of the wheel and tire resulted in a somewhat higher dust charging rate (+13.3 kv/sec) than other comparable dust charging rates. Such rotation would provide a relative charge-carrier velocity on the advancing top of the wheel of about three times the observed wreckage speed of 45 miles per hour. At the higher velocities of the snow charging experiments described in reference 10, charging current was found to increase nearly as the cube of the airspeed. Thus, the higher relative velocity due to wheel rotation may be responsible for the higher charging rate. The possibility also exists that wheel rotation allows time for the accumulated charge to distribute on the rubber surface and leak to the metal parts, which may also be effective in increasing the charging rate of the rotating wheel and landing gear. However, in 21 simulated take-off accidents, few wheels rotated appreciably after impact with the barrier used to remove the landing gear, and this value is not considered typical of these crashes. No appreciable effect on charging rate was noted by varying the relative velocities of the dust blown at the complete landing gear over the narrow range studied from 45 to 65 miles per hour. (Compare experimental configurations 1(a) and (d) of table I.) Maximum charging rates did not increase significantly with velocity (+5.1 kv/sec against +5.5 kv/sec converted to 1 g/ft), nor was the rate of potential increase greater per gram of dust blown at the higher velocity.

Wreckage material (metal as compared with rubber) appeared to cause a small, twofold change in dust charging rate. Metal parts of the landing gear, with the tire removed, showed a maximum charging rate of

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+10.2 kilovolts per second under otherwise similar conditions in which the landing gear with the tire charged at +5.1 kilovolts per second (experimental configurations 3(a) and 1(a) of table I). Only 5 percent of this increase might be attributed to the 5-percent lower capacitance that resulted from removing the tire. A rubber-sheathed axle and wheel (shown in fig. 3), upon which were mounted, in turn, static-conducting and nonstatic-conducting rubber tires, had a maximum charging rate of the same magnitude as similar dust charging experiments, although the maximum potential increase rate showed a twofold increase to +11.2 kilovolts per second (experimental configurations 1(a) and 4(a)). Halving the potential increase rate is required to obtain a comparable charging rate, since the charged system had only half the capacitance of the other simulated-wreckage experimental configurations.

Fuel-mist charging of the metal landing gear with the tire removed produced the smallest maximum charging rates, -3.9 kilovolts per second (configuration 3(b) in table I). Charging rates nearer the mean of the maximums listed in table I might have resulted had a wider range of day-to-day uncontrolled variables been encountered by conducting more experiments.

During all 51 experiments described in the preceding discussion and in table I, in which the effects of himidity, temperature, surface resistivity, and so forth, which are affected by uncontrolled random weather conditions, but which were such as might exist in a crash, the maximum charging rate was -38 kilovolts per second at a charge-carrier concentration of 1 gram per cubic foot (table I). This charging rate resulted from blowing a fuel mist of 0.14 gram per cubic foot over the landing-gear assembly at 45 miles per hour (configuration 1(b)). Under conditions also likely to occur in an airplane crash, clay dust produced a charging rate of 10.2 kilovolts per second at 1 gram per cubic foot on the metal struts and wheel from which the rubber tire was removed (configuration 3(a)). These maximum values, which are considered to represent the order of magnitude of charging that could be expected for a unit charge-carrier concentration within the range of tabulated conditions, will be used in subsequent estimates related to the size of wreckage required for a hazardous accumulator of electrostatic ignition energy.

Electrostatic Ignition Hazard

Since it has been shown that electrostatic charging of flying wreckage is possible, it is necessary to obtain some indication of the resulting fire hazard. The preceding results and discussion have shown the extent to which electrostatic energy may be generated on flying wreckage by clouds of charge carrier dispersed by the sliding airplane. By the application of this and other pertinent information, it is possible to make estimates of the energy collected by the landing gear during the crash in which ignition occurred, and of the minimum size of wreckage necessary to collect sufficient energy to be hazardous. In order to make these estimates, it is convenient to establish a plausible value for the minimum ignition energy required by an electrostatic spark to ignite hydrocarbon fuels.

After an estimate is made of the minimum hazardous size of flying wreckage, it is possible to obtain an over-all indication of the frequency of occurrence of electrostatic ignition hazards by studying the full-scale crash pictures and estimating the frequency of flying wreckage of hazardous size. The order of discussion of these subjects will be as follows:

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(1) Estimate of electrostatic energy required for ignition

(2) Estimate of energy accumulated in crash ignition incident

(3) Estimate of minimum size of wreckage necessary to generate ignition energy

(4) Frequency of occurrence of electrostatic ignition hazards in controlled crash investigations

(5) Summary of electrostatic ignition hazard in airplane crash fires

Estimate of required electrostatic ignition energy. - The minimum spark ignition energy of an inflammable mixture is defined for capacitance sparks in reference 11 as the total energy stored in an electric circuit at the initiation of the weakest spark just capable of igniting the mixture. The quantity of energy required increases rapidly as the following factors deviate from the optimum: the combustible-mixture composition, velocity, and pressure, the electrode spacing and configuration, and the spark duration. The electrode composition and the voltage appear to have little effect on the minimum ignition energy. Although, under precise laboratory control, as little as 0.1 millijoule will ignite quiescent hydrocarbon-air mixtures (see ref. 1), greater energies are required for conditions that deviate slightly from the optimum. Other factors may also operate to require greater quantities of stored energy on the wreckage at the instant of discharge. Although dust in the air is an electrostatic generating agent, it may also act to prevent ignition. The characteristics of the electrodes (the wreckage and the ground), their total electrical discharge paths, and factors such as mixture composition and velocity (summarized in ref. 11) operate to require larger ignition energies. It was experimentally determined that optimum composition propane-air mixtures, flowing at 70 to 90 milliliters per second from the 1/2-inch-diameter jet shown in figure 5 required a minimum energy of 1.4 millijoules (fig. 8). Similarly, sparks to clay soil from the nozzle shown in figure 4 required a stored energy of 1.2 millijoules to ignite the flowing propane-air mixture. In view of the improbability of the simultaneous meeting of all the many required optimum ignition conditions necessary to achieve 0.1-millijoule ignitions and in view of the 1.4- and 1.2-millijoule ignitions obtained when only mixture composition was optimum, an energy of 1 millijoule is considered to be a conservative "plausible minimum ignition energy." This value will be used in the succeeding discussion.

Estimate of electrostatic energy accumulated in crash incident. - In order to determine whether the landing-gear ignition incident described in the INTRODUCTION and in reference 1 was the result of borderline charging conditions, estimates were made of the electrostatic energy accumulated on the landing gear in the incident. These estimates are based on the following conditions and assumptions derived from the crash-fire investigations and the previously described charging-rate studies:

(1) The landing gear flew through a dust cloud estimated to contain 0.6 gram per cubic foot of clay dust at 45 miles per hour for 1.08 seconds before landing in an area of fuel spillage that it ignited (fig. 1). Contact of the tire with the ground at the end of the first bounce, which preceded this flight, harmlessly discharged any charge resulting from this first flight through dust and fuel mist.

(2) The charging current to be expected on the flying landing gear is the same as in the previously described charging-rate experiments, converted for dust density. This highest dust charging rate was +5.1 kilovolts per second at 1 gram of dust per cubic foot of air in the experimental configuration (1(a)) that was most like the crash conditions. This configuration consisted of dust alone in a 45-mile-per-hour air stream blowing at the completely severed landing gear, which had a capacitance, suspended in a metal frame, of 150×10^{-12} farad. The electrostatic voltmeter and connecting lead had capacitances of 8×10^{-12} and 42×10^{-12} farad, bringing the total capacitance of the system to 200×10^{-12} farad. At the 0.6-gram-per-cubic-foot estimated dust concentration, the charging rate for the capacitance of this system would be 3.06 kilovolts per second. The charging current is about 0.6 microampere by the equation

$$i = CV/t \tag{1}$$

where i is the current in amperes, which would charge C, the capacitance in farads, to the potential V, which is also the potential increase in volts; and t is the time of potential increase in seconds.

(3) The capacitance of the flying severed landing gear, which will be used to calculate its accumulated energy, is estimated to be

130×10^{-12} farad by the relation given in reference 3. This relation states that the capacitance of an object in micromicrofarads is roughly 1.1 times its radius or one-half its greatest dimension in centimeters. This value is slightly less than the 150×10^{-12} farad measured capacitance of the severed landing gear when suspended for charging experiments. A measured capacitance to ground in excess of the estimated free-flying capacitance is to be expected because of the proximity of the grounded metal suspension structure.

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From the preceding assumptions, the flying landing gear with 130×10^{-12} farad capacitance charging at 0.6 microampere for 1.08 seconds would accumulate a potential of 5.0 kilovolts. By the relation

$$W = \frac{1}{2} CV^2 \tag{2}$$

where

W energy, joules

C capacitance, farads

V potential, volts

this 5.0-kilovolt potential would represent 1.6 millijoules of stored electric energy. This energy exceeds the chosen value of plausible mininum ignition energy, and it can thus be considered as additional evidence that this crash fire was ignited by an electrostatically generated spark; however, the conditions appear to have been borderline for such an ignition.

If the crash conditions had been altered slightly so that the severed landing gear had traveled through fuel mist alone, instead of dust, the charging experiments (table I) show that the severed landing gear might have charged at -38 kilovolts per second at 1 gram of fuel per cubic foot of air. At the 0.6 gram per cubic foot of air concentration of charge carrier estimated to be present behind the airplane, this charging rate is equivalent to a current of 4.56 microamperes. In the 1.08 seconds available for charging at this maximum rate determined for fuel mist, 38 kilovolts and 93 times minimum ignition energy would have been accumulated. Thus, crash conditions can exist that would result in wreckage accumulating many times the chosen plausible ignition energy. Under such circumstances, optimum conditions for ignition would not be required and the probability of fire would be increased.

Estimated minimum hazardous wreckage size. - The minimum size of wreckage that presents an electrostatic ignition hazard may be estimated on the basis of the following assumptions:

(1) The relative speed between detached wreckage and the charge-carrier cloud is about half take-off speed, 45 miles per hour in this case.

(2) At this speed and at a charge carrier-density of 0.6 gram per cubic foot, the maximum charging current (fuel mist alone) on a landing gear of 15 square feet of frontal area was found to be 4.56 microamperes, or 0.304 microamperes per square foot of frontal area when fuel mist was blown at the complete severed landing gear.

(3) The wreckage is of spherical shape with a capacitance in microfarads (ref. 3) of 1.1 times one-half the greatest dimension in centimeters (16.78 multiplied by diam. in ft). Potentials and energies generated are dependent upon the frontal area and the capacitance of flying objects which, for a sphere, are functions of the diameter.

(4) The charging time or time of flight of an object, if it is to be in the charge-carrier cloud for the maximum time, is the time of rise and free fall from the top of the cloud.

With these assumptions, the rate with which the wreckage potential increases when flying through a charge-carrier cloud can be evaluated by equation (1):

$$V = it/C$$

The terms on the right side of this equation can be evaluated as follows in terms of the effective wreckage diameter and the trajectory height:

$$i = 0.304 \text{ µamp/sq ft (from assumption 2)} \times \frac{\pi d^2}{4}$$

where d is the greatest wreckage dimension or diameter in feet;

$$t = 0.499 \sqrt{H}$$

where H is the height of the trajectory within a charge-carrier cloud in feet;

$$C = 16.78d \times 10^{-12} \text{ farad (from assumption 3)}$$

Combining the various constants gives the final potential of the wreckage:

$$V = 7110d \sqrt{H} \text{ volts} \tag{3}$$

These terms also may be substituted in a form of the energy equation (2), in which potential increase V is replaced by its equivalent in current, time, and capacitance

$$W = \frac{1}{2}\frac{(it)^2}{C}$$

$$= \frac{\left[\left(0.304\pi \frac{d^2}{4} \times 10^{-6}\right)\left(0.499\sqrt{H}\right)\right]^2}{2(16.78d \times 10^{-12})} \qquad (4a)$$

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in order to solve for the energy accumulated on spherical-shaped wreckage:

$$W = 0.000424d^3H \qquad (4b)$$

The minimum diameters of spherical wreckage that would, under the preceding assumptions, accumulate a hazardous ignition energy and potential are plotted in figure 7 as a function of trajectory height in a charge-carrier cloud. In the crashes observed in this investigation, fuel and dust clouds rarely extended above 12 feet during the time crash-detached wreckage was falling. Curve A ($d = 1.33H^{-1/3}$ from eq. (4b)) indicates that a 12-foot-high trajectory requires spherical wreckage of 0.6-foot diameter to accumulate a plausible minimum ignition energy of 1 millijoule. Lower trajectory heights would require larger wreckage diameters. The diameter and the trajectory values corresponding to the literature minimum ignition energy of 0.1 millijoule are given by curve B ($d = 0.62H^{-1/3}$). Thus, wreckage smaller than a sphere of 0.3-foot diameter in a 12-foot-high trajectory is incapable of producing ignition sparks, and hazardous diameters probably must exceed 0.6 foot.

Although minimum ignition energies may have been accumulated, the potential must also exceed 4000 volts. This potential is necessary to spark across gaps of over 0.05 inch. Gaps smaller than 0.05 inch quench low-energy capacitance spark ignitions. Curve C ($d = 0.56H^{-1/2}$) shows that the diameters and the trajectory heights required to produce this potential are smaller than those required to produce minimum ignition energy. Therefore, if the trajectory height and the diameter of wreckage suffice to accumulate ignition energy (1 or 0.1 mj), the potential will spark across a gap that exceeds the quenching distance. Thus, ignition is not limited by inadequate potential if the necessary energy has accumulated.

The assumption of spherical shape of wreckage in the preceding analysis probably leads to estimates of wreckage diameter or span that are smaller than actually required to accumulate sufficient ignition energy.

Nonspherical-shaped wreckage can never have more, and usually will have less, frontal area than spherical wreckage of the same greatest dimension. Both frontal area and capacitance, however, are functions of diameter. Inspection of the derivation of equation (4a) will show that, while the energy accumulated is only a first-power inverse function of the diameter term derived from capacitance, the energy accumulated is a direct fourth-power function of the area-dependent diameter term derived from charging current and potential. Therefore, it is likely that deviations of wreckage shape from the assumed spherical shape would reduce the
2812 charge-accumulating effect of area much more than decreasing capacitance would increase the potential and energy of the charge.

During the rate-of-electrification experiments, it was noted that, in the majority of recorded tests, the voltage was limited to about 17 kilovolts; although in many experiments the range of the 20-kilovolt meter was exceeded. In a few cases, it appeared that discharges occurred across the sphere gaps set at 30 kilovolts, but these observations were never recorded photographically. It appeared likely, therefore, that corona (silent glow) discharge might limit the potential generated on flying wreckage and require that the size of hazardous wreckage be larger than estimated in the preceding paragraphs. While the properties of corona discharge are well-known for power-transmission and radiation-counter applications, data applicable to direct-current problems involving wide spacings are limited. The data of references 10 and 12 to 14 indicate that, under crash conditions, significant corona discharge currents may commence to flow from sharp points and edges of fractured wreckage when potential gradients in excess of 500 volts per centimeter are attained. Corona discharge currents, once the onset gradient is attained, can be many times larger than the maximum experimental electrification current measured in this study. It is believed that corona discharge may appreciably reduce the energy available for ignition in the time during which wreckage falls from a height above ground at which the corona-onset potential gradient is reached to a height at which the spark occurs. Thus the effect of corona discharge may also operate to require larger wreckage to accumulate a plausible minimum ignition energy than is indicated by the relation $d = 1.33H^{-1/3}$.

Occurrence of electrostatic ignition in full-scale crash investigations. - In order to evaluate the preceding estimate of minimum size and trajectory of wreckage that constitute an electrostatic ignition hazard, an inspection was made of the motion pictures and maps of wreckage distribution of 21 full-scale crashes. These crashes were conducted as described in reference 1 to simulate take-off accidents. Although motion pictures were taken from seven directions, the wakes behind the airplanes were photographed only incidentally. These photographs, however, gave at least some picture of the charge-carrier clouds raised behind the airplane during each crash. Only detached wreckage of somewhat greater span than given by curve A (fig. 6) could be observed in the motion pictures. A count was made of wreckage exceeding 2-foot greatest dimension that flew through charge-carrier clouds to land in areas of fuel spillage and thus became potential ignition sources. Of the hundreds of pieces of wreckage detached from airplanes during these 21 crashes, only 12 such pieces of wreckage (larger than 2 ft) landed in areas of fuel spillage to become potential ignition sources. Of these potential ignition sources only the largest, the detached landing gear previously discussed, ignited the spilled fuel. This survey thus implies that (1) the minimum hazardous wreckage sizes are significantly larger than the estimate $d = 1.33H^{-1/3}$ (fig. 6) indicates; and (2) wreckage constituting an electrostatic ignition hazard is infrequent compared with the occurrence of other airplane-crash ignition sources. 2812

Summary of hazard. - It has been shown on the basis of assumptions that the electrostatic energy accumulated on detached airplane wreckage flying at expected velocities through clouds of clay dust and fuel mist is a function of the cube of the diameter and of the trajectory height. For minimum (laboratory) ignition energy and with a trajectory height at the top of the highest expected dust or fuel clouds, this equivalent spherical diameter is certainly over 0.3 foot and probably exceeds 0.6 foot in airplane crashes at present take-off speeds. Among the hundreds of pieces of wreckage observed in 21 full-scale crashes, only 12 landed in combustible areas and were estimated to have accumulated more than a plausible minimum ignition energy. That only the largest one of these 12 pieces of wreckage that were counted as hazardous ignited spilled fuel may be attributed to several causes: the assumptions of the preceding estimate, the deviation of conditions for ignition too far from the optimum, and the loss of the necessary energy through corona discharge.

Consideration of the minimizing nature of the assumptions of this analysis and of the results from the study of crashes indicates that the hazard of electrostatic spark ignition in airplane crashes is small compared with the hazards presented by the large number of ignition sources described in reference 1.

Investigation of Protective Coating

The literature survey described in the INTRODUCTION showed that the most promising of several methods of reducing static spark ignition hazards in an airplane crash is that of coating structures likely to become flying wreckage with a material of high dielectric strength.

Requirements of protective coating. - Sparks of sufficient power for ignition from either the surface of the insulating coating or the charge induced on the underlying metal must be prevented by the surface and volume resistivity properties of the coating. For this reason the breakdown voltage of the surface resistance must be sufficient to prevent the rapid discharge of an area condensing a charge capable of delivering the plausible ignition energy (1 mj). Puncture discharge from the metal through the insulating material must not occur until the spark gap is so small that spark ignition is quenched or the spark is submerged in the coating. Finally, a satisfactory insulating coating must be capable of retaining its electrical properties under the conditions of its use.

Comparison of volume resistivities (dielectric strengths) of plastic coating materials in reference 15 reveals no particularly outstanding material; but many, applied in practical thickness, can be expected to have adequate breakdown voltages. Thus, surface resistance under high dielectric stress became the principal criterion in the choice of a coating material, especially since it had been thought that the surface of even the best coating might act as a conductor at high potentials and deliver its electrostatic charge in an ignition spark. Since, except for a few substances such as waxes, surface resistivity is stated in reference 3 to change by a factor of 10^6 with a change in relative humidity from 30 to 80 percent, polyethylene synthetic plastic was chosen to test as one example of the materials that may provide an adequate protective coating. This material is chemically similar to paraffin wax but has more suitable physical properties. However, other materials such as polytetrafluoroethylene may give adequate or better protection. For example, even rubber tires were found to present no spark ignition problem, although the preceding tests show that rubber surfaces can be expected to charge like metal in a stream of impinging fuel mist or clay dust. At over 20 kilovolts, the tire and rubber would only slowly and partially discharge when contacted with a grounded electrode. No spark could be seen or heard, nor would the silent discharge ignite an inflammable propane-air mixture. Therefore, no protective coating appears to be required for either "static conducting" or standard rubber tires, although thinner rubber coverings such as de-icing boots may require coating to prevent electrical puncture and discharge of the underlying metal.

Evaluation of polyethylene. - Polyethylene was applied to several hollow steel spheres by two methods. In one method, called flock-coating, the powdered polyethylene was fused to a sphere at a temperature above the melting point. In the second method, polyethylene powder was flame-sprayed on a heated sphere. Flame-spraying produces a thinner, more uniform coating but, if improperly applied, may contain specks of conducting carbon. The thickness of the coating on the spheres varied from 0.006 to 0.094 inch. The largest available spheres that could be conveniently mounted on the electrostatic voltmeter as shown in figure 5 were selected. These spheres were $12\frac{1}{2}$ inches in diameter and were made of hollow welded 1/8-inch steel with a vapor-blasted finish.

To evaluate a coating for ignition-inhibiting properties requires that it be subjected to voltages of at least the order reached in the dust and fuel blowing tests described in preceding sections. The object on which the coating is to be tested must be large enough to store many times the 1-millijoule plausible ignition energy in order to ensure the possibility of obtaining ignition sparks. The surface of the $12\frac{1}{2}$-inch hollow steel sphere is adequate in this respect, since it had a capacitance of 27.5×10^{-12} farad, which is capable of storing 7 millijoules or seven times plausible ignition energy at the +27.5 kilovolts available from the available d-c power supply. A spark from the uncoated-sphere and voltmeter capacitance of 36×10^{-12} farad would consistently ignite a flowing mixture of propane and air at 8.5 kilovolts or 1.4 millijoules. 2812

Potentials of the $12\frac{1}{2}$-inch polyethylene-coated sphere and the corresponding energies at which ignition trials were made are plotted as a function of polyethylene thickness at the point of discharge in figure 8. It will be noted that all ignitions, indicated by circles, fall in a region above a line drawn from 8.5 kilovolts on an uncoated sphere to about 28 kilovolts on an area with a 0.020-inch coating. Below this line is a "safe" region in which the polyethylene coating was thick enough to prevent ignitions, as indicated by the square symbols, at the applied potentials. Polyethylene coatings thicker than 0.020 inch thus offer promise of protection against electrostatic spark ignition for the order of potentials generated in previously described experiments.

Trials with a heavier (0.094-in.) coating and the spherical electrode produced only slow, nonluminous discharges. Luminous discharges were produced in these cases only by driving a pointed electrode through the coating. The spark appeared to be submerged in the polyethylene and, in ten trials, would not ignite the propane-air mixture.

In order to ensure that contaminations of the polyethylene surface with dust and fuel would not seriously alter these results, discharges of experimental electrifications of the sphere with a 0.094-inch polyethylene coating were attempted. Dust or fuel, or both, were blown at the insulated sphere suspended as shown in figure 9. Dust- and fuel-generated charges of over 20 kilovolts thus obtained would not discharge at a rate sufficient to cause ignition from or through the surface of the polyethylene.

Some detached crash wreckage may discharge ignition sparks in spite of an insulating coating if bare areas, which may be produced as the wreckage is torn from the main structure, attain a suitable spark-gap to ground before slow discharge through the coating inerts the wreckage.

SUMMARY OF RESULTS

From measurements of electrification rates of airplane wreckage by dust and fuel mist and from previous data, the following results and estimates have been obtained from which the electrostatic ignition hazard in airplane crashes may be judged:

1. In simulated-crash electrification experiments at take-off speeds, it was found that energy accumulated on airplane wreckage is a linear function of the mass of clay dust or fuel mist intercepted. Wreckage acquires a positive charge from clay dust and a negative charge from fuel mist. The type of wreckage material appears to have minor effects on electrification. Clay dust and fuel mist blown together at the wreckage produce less electrification than either alone. A maximum charging current of 0.304 microampere per square foot of frontal area was obtained in experiments with airplane parts when 0.6 gram of clay dust or fuel mist per cubic foot of air was blown at 45 to 65 miles per hour.

2. Insulating coatings having high dielectric strength and surface resistivity (polyethylene, polytetrafluoroethylene) offer promise of protection against electrostatic spark ignition.

3. The greatest dimension of wreckage must exceed 1.33 times the reciprocal cube root of the trajectory height in feet in order to accumulate a plausible minimum ignition energy of 1 millijoule. For the greatest height of dust or fuel cloud observed in the full-scale crashes (12 ft) during the time wreckage fell, this value exceeded 0.6 foot.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 26, 1953

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TABLE I. - RATES OF POTENTIAL INCREASE PRODUCED BY BLOWING CLAY DUST AND HYDROCARBON FUEL MIST AT INSULATED AIRPLANE PARTS

Experimental configuration	Capacitance of system,[a] ±5 percent, farad	Charge carrier		Number of experiments	Maximum potential increase rate, kv/sec	Concentration of charge carrier in air stream at maximum kv/sec, g/cu ft	Maximum potential increase rate corrected to 1 g/cu ft, kv/sec
		Material	Impact velocity, mph				
1. Landing-gear struts, wheel, and rubber tire	200×10^{-12}	a. Clay dust	45	17	+5.7	1.1	+5.1
		b. JP-3 fuel	45	4	-5.3	0.14	-38
		c. JP-3 fuel with clay dust	45	6	[b]0.54	(c)	(c)
		d. Clay dust	65	9	+2.9	0.53	+5.5
2. Landing-gear struts, wheel, and rubber tire. Wheel and tire rotating 300 rpm	200×10^{-12}	Clay dust	45	3	+8.7	0.68	+13.3
3. Metal parts of landing gear and wheel (rubber tire removed)	[d]200×10^{-12}	a. Clay dust	45	3	+4.3	0.42	+10.2
		b. JP-3 fuel	45	2	-0.54	0.14	-3.9
4. Rubber tire and rubber-sheathed wheel	100×10^{-12}	a. Clay dust	45	5	+7.5	0.67	+11.2
		b. JP-3 fuel	45	2	-2.5	0.19	-13.2

[a]Includes capacitance to ground of simulated wreckage, electrostatic voltmeter, and connecting lead.
[b]Polarity not measured. Positive and negative charged wreckage are both likely.
[c]Dust rate not measured because of fire hazard to personnel.
[d]Tire removal decreased capacitance 5 percent.

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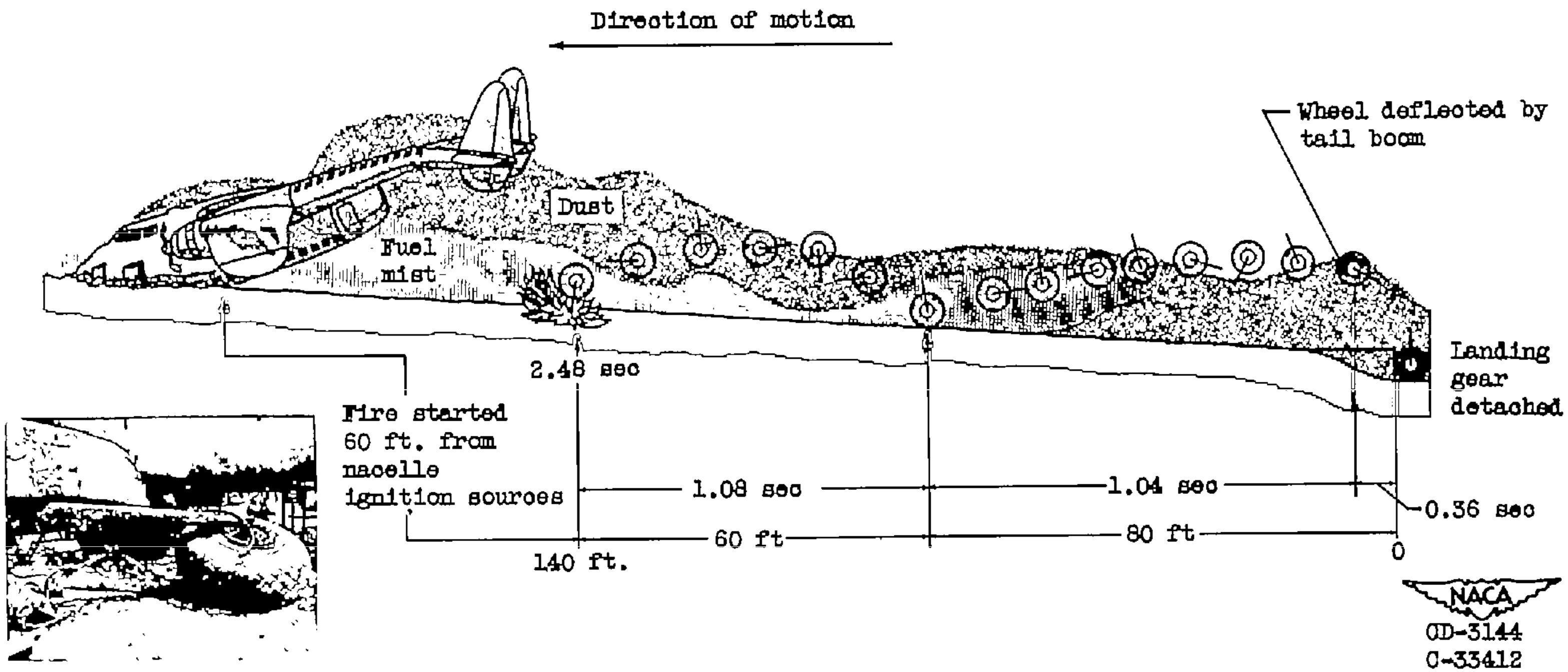

Figure 1. - Trajectory of detached landing gear before ignition of airplane crash fire.

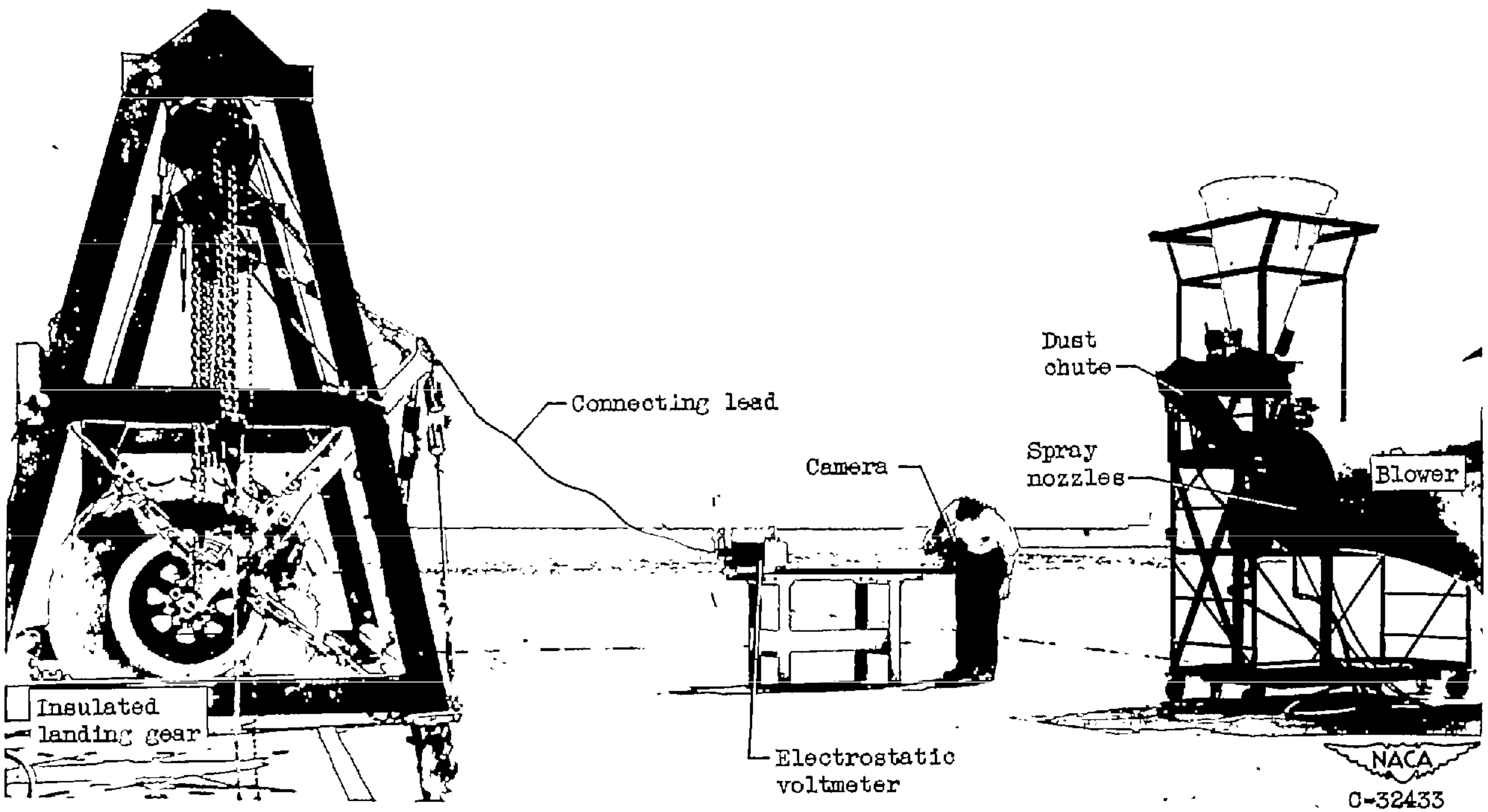

Figure 2. - Experimental equipment used to study electrostatic charging of airplane wreckage. Capacitance, farads: landing gear, 150×10^{-12}; electrostatic voltmeter, 8×10^{-12}; connecting lead, 42×10^{-12}; total system capacitance, 200×10^{-12}. Resistance, about 10^{12} ohms.

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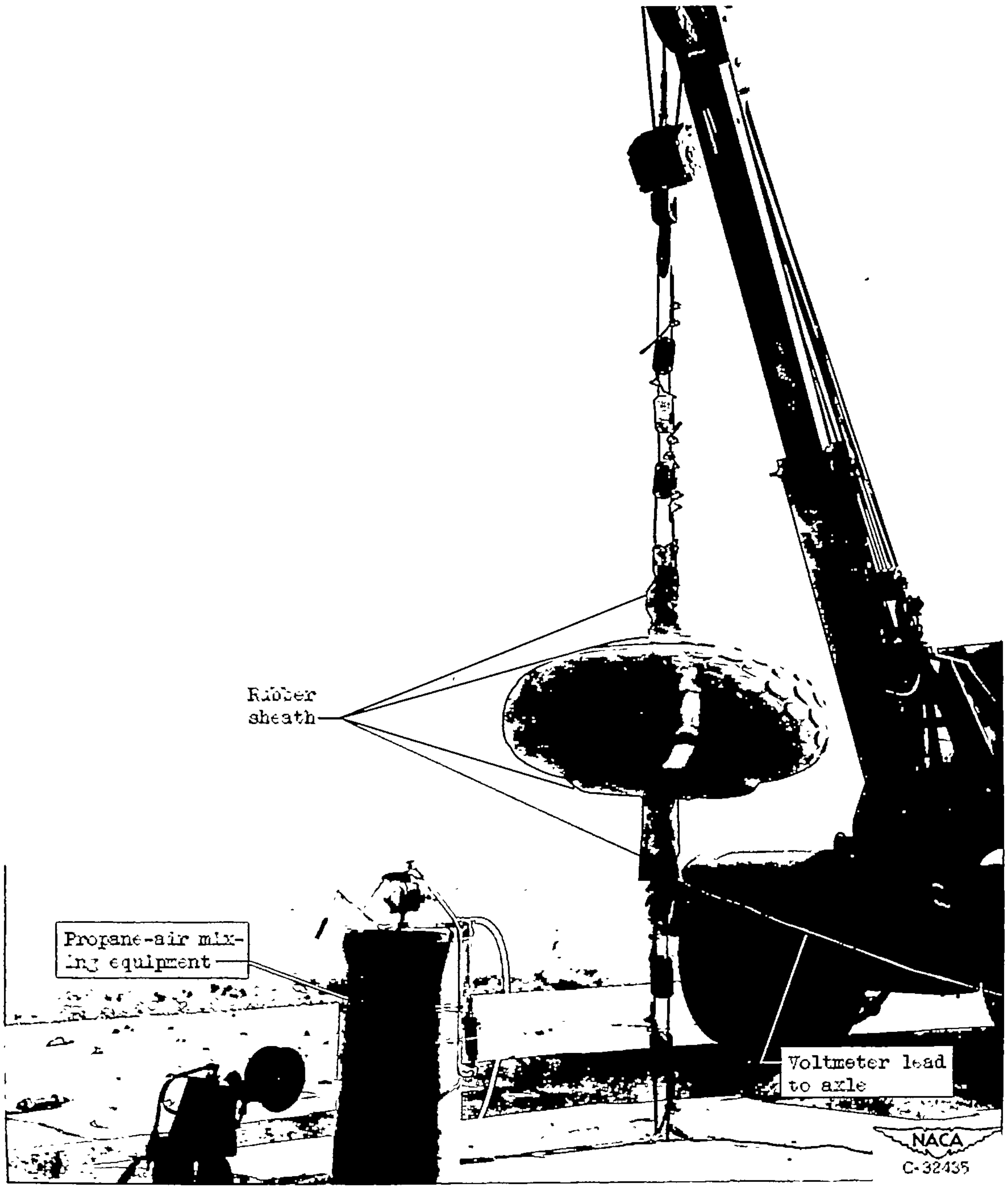

Figure 3. - Insulated suspension of tire and rubber-sheathed wheel and axle. Capacitance, 100×10^{-12} farads.

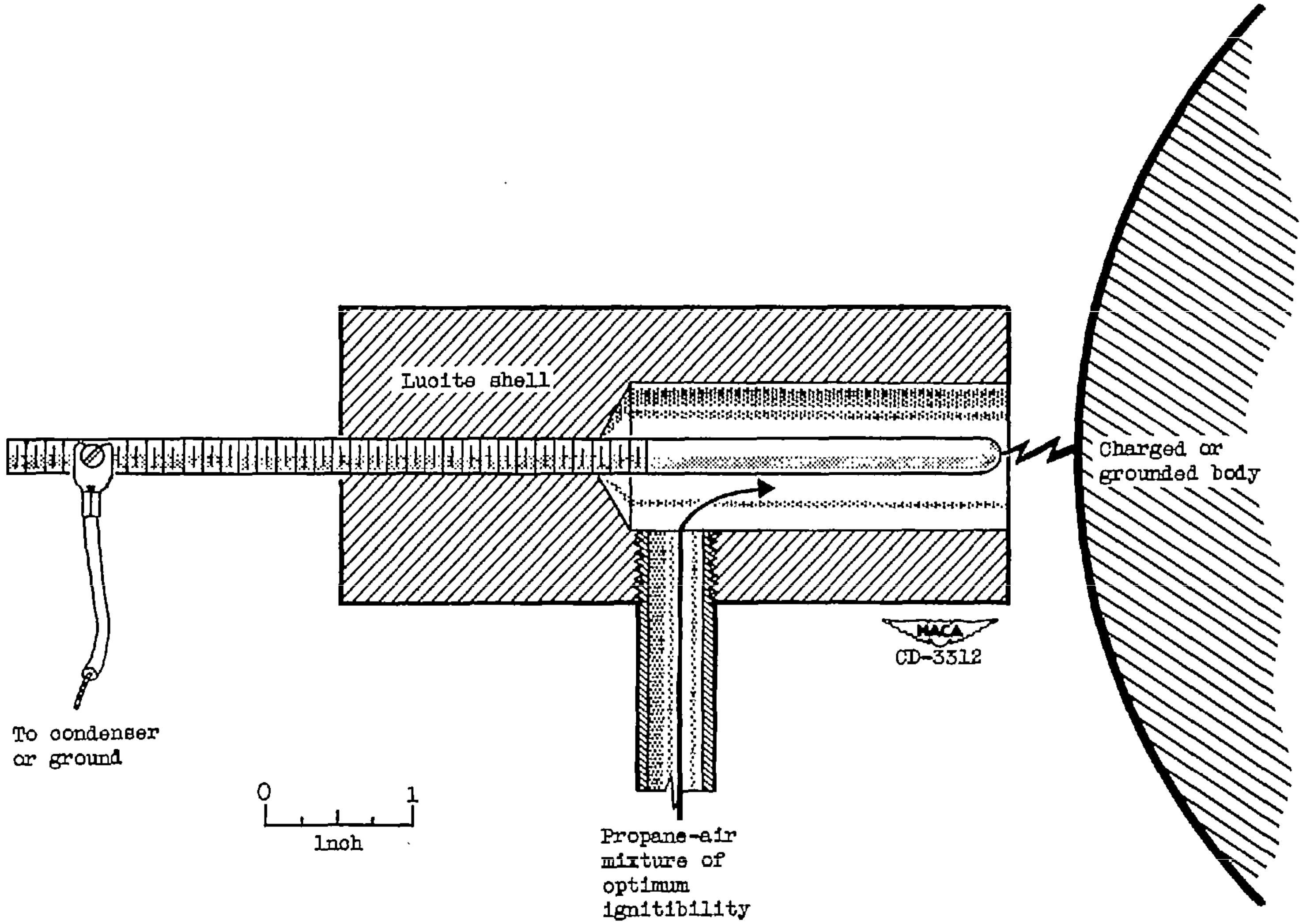

Figure 4. - Ignition-capability discharge probe.

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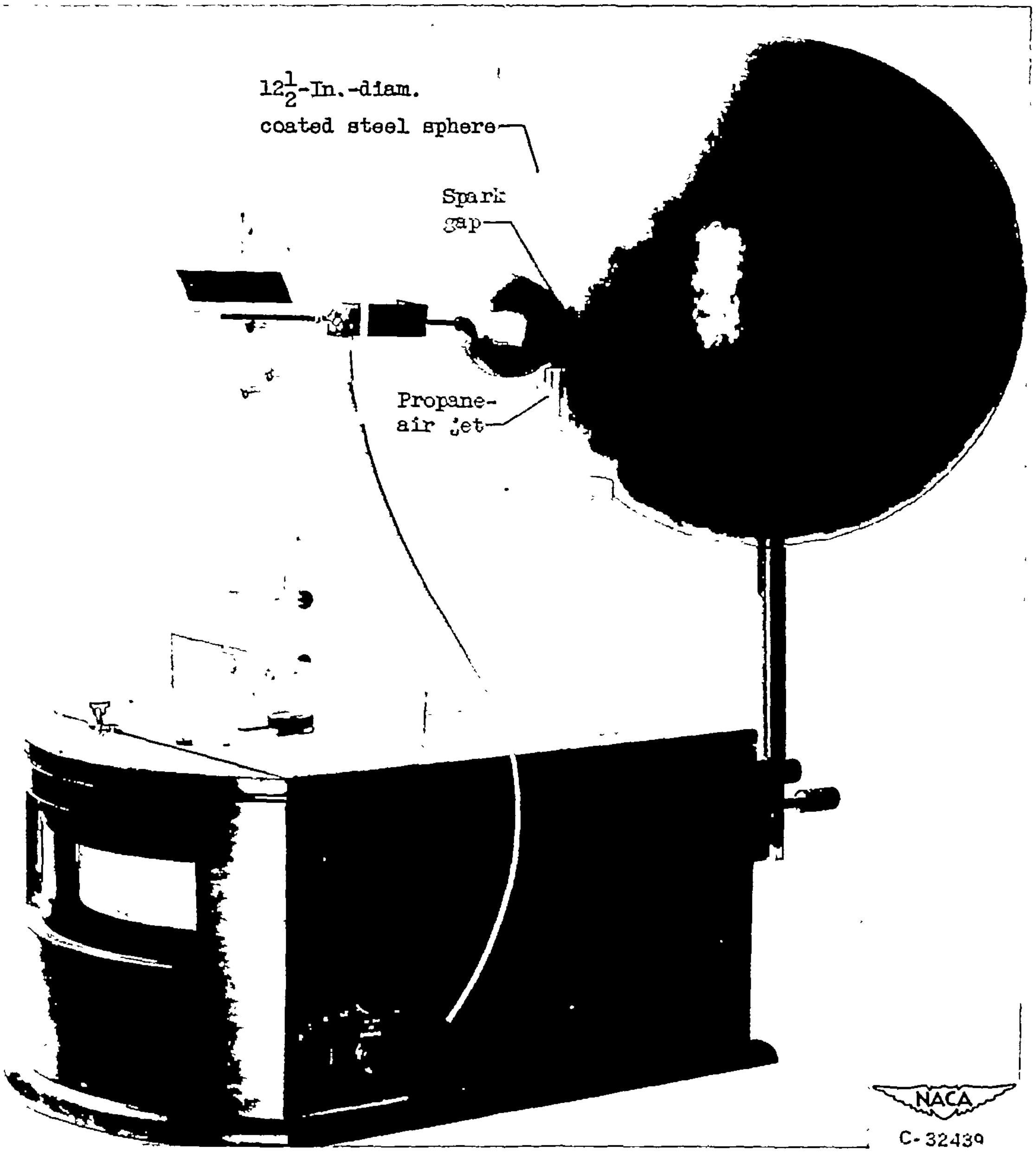

Figure 5. - Protective-coating test equipment. Polyethylene-coated $12\frac{1}{2}$-inch-diameter sphere mounted on electrostatic voltmeter. Grounded discharge electrode, 2.46-inch-diameter aluminum sphere. Capacitance of system, 36×10^{-12} farad; capacitance of meter without sphere, 8×10^{-12} farad.

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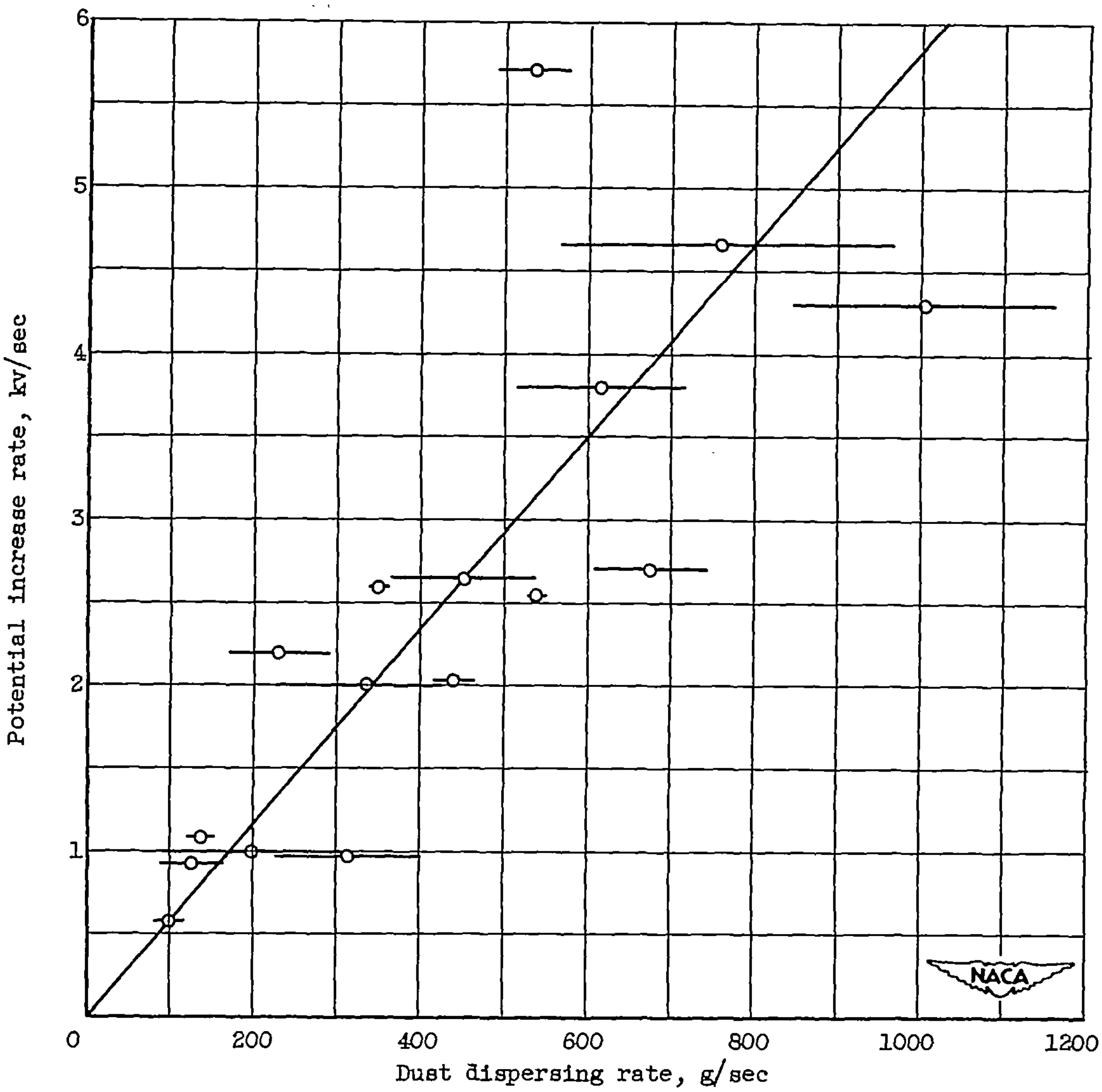

Figure 6. - Maximum potential increase rate as function of dust dispensing rate. Clay dust blown at 45 miles per hour at insulated landing-gear struts, wheel, and tire. Capacitance, 200×10^{-12} farad.

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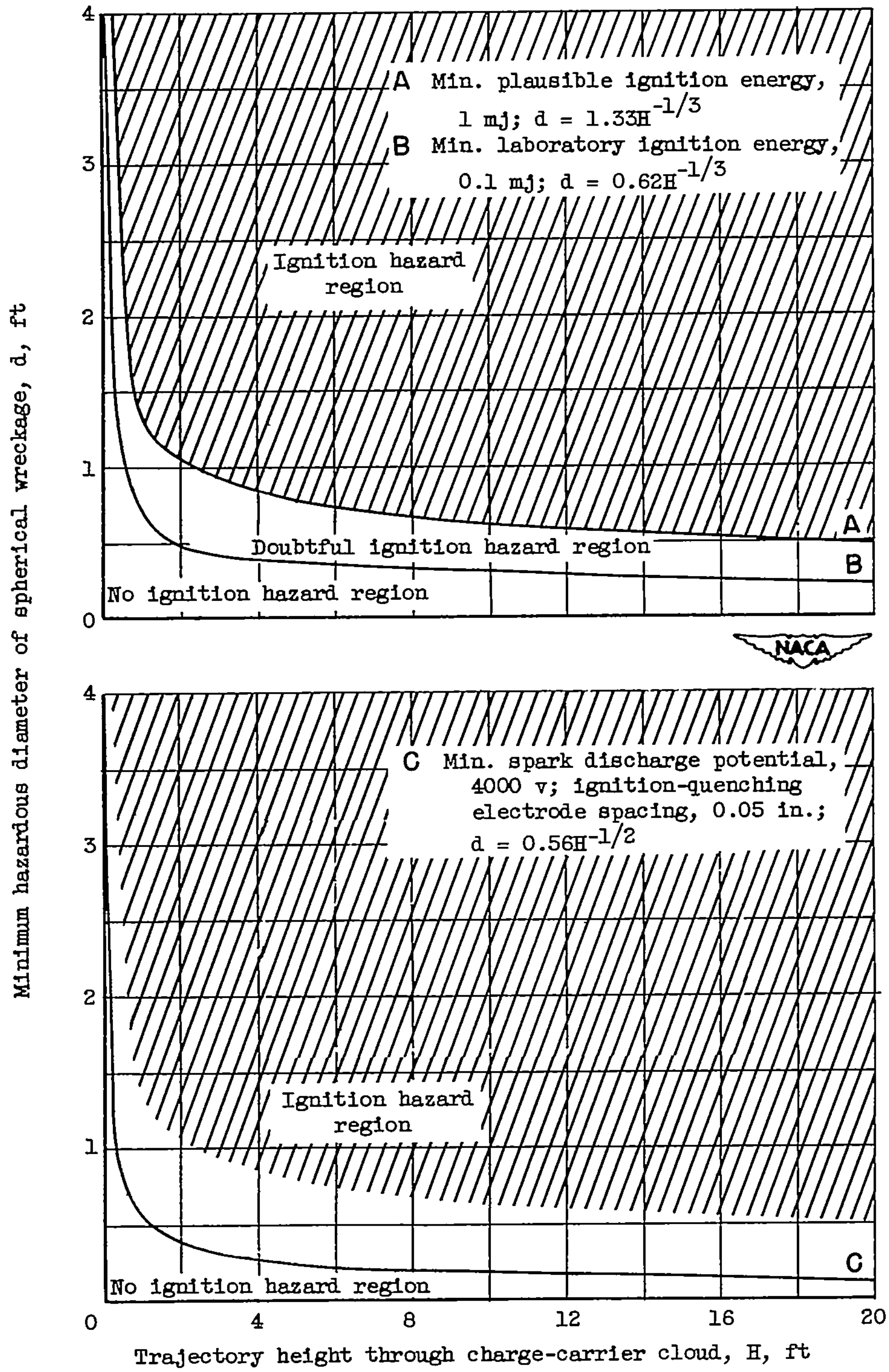

Figure 7. - Minimum hazardous diameter of spherical wreckage as function of trajectory height through charge-carrier cloud at 45 miles per hour, charging at 0.304 microampere per square foot of frontal area per second.

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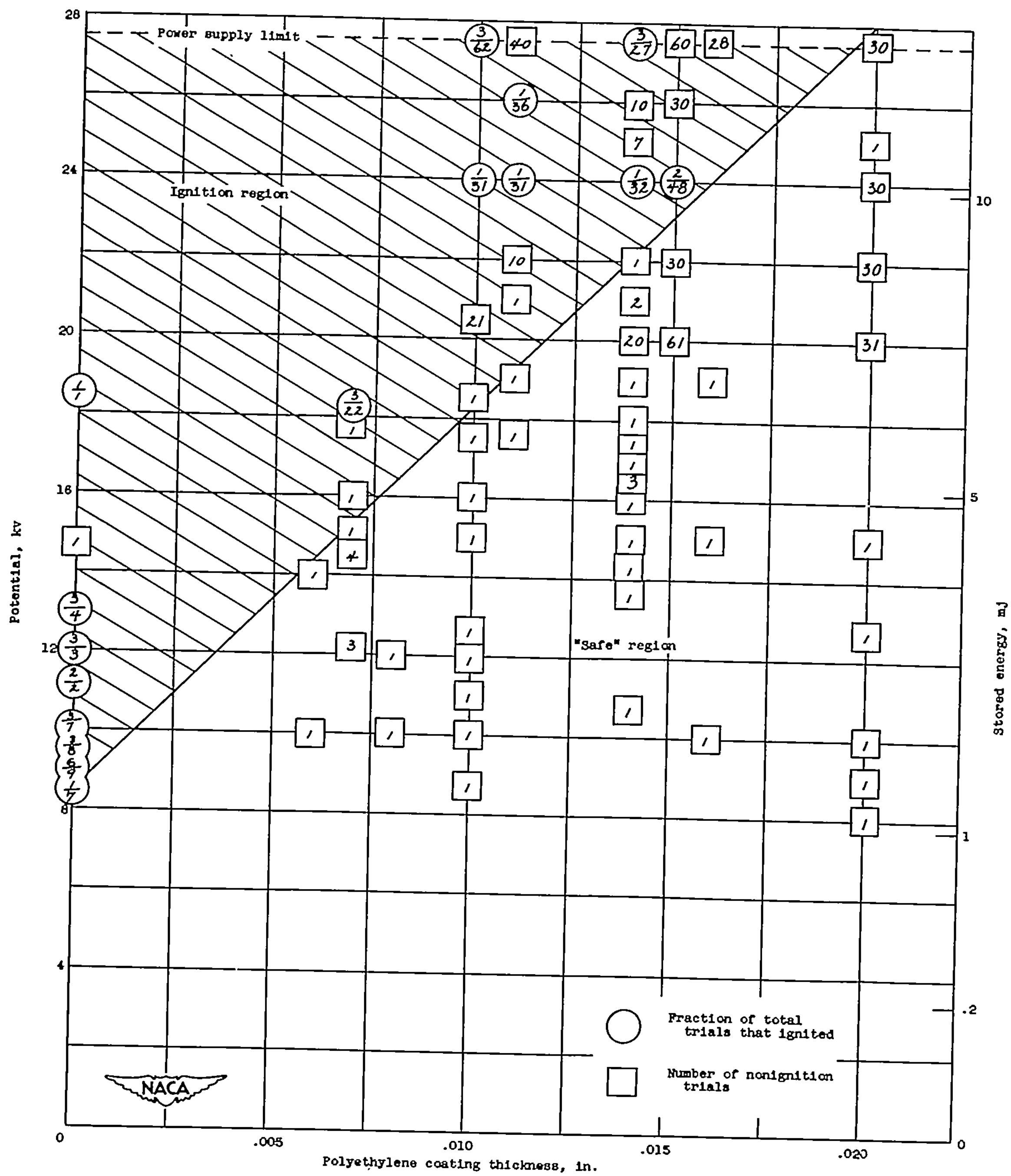

Figure 8. - Ignition spark potential as function of polyethylene thickness coated on $12\frac{1}{2}$-inch-diameter steel sphere. Capacitance of sphere and meter, 36×10^{-12} farad.

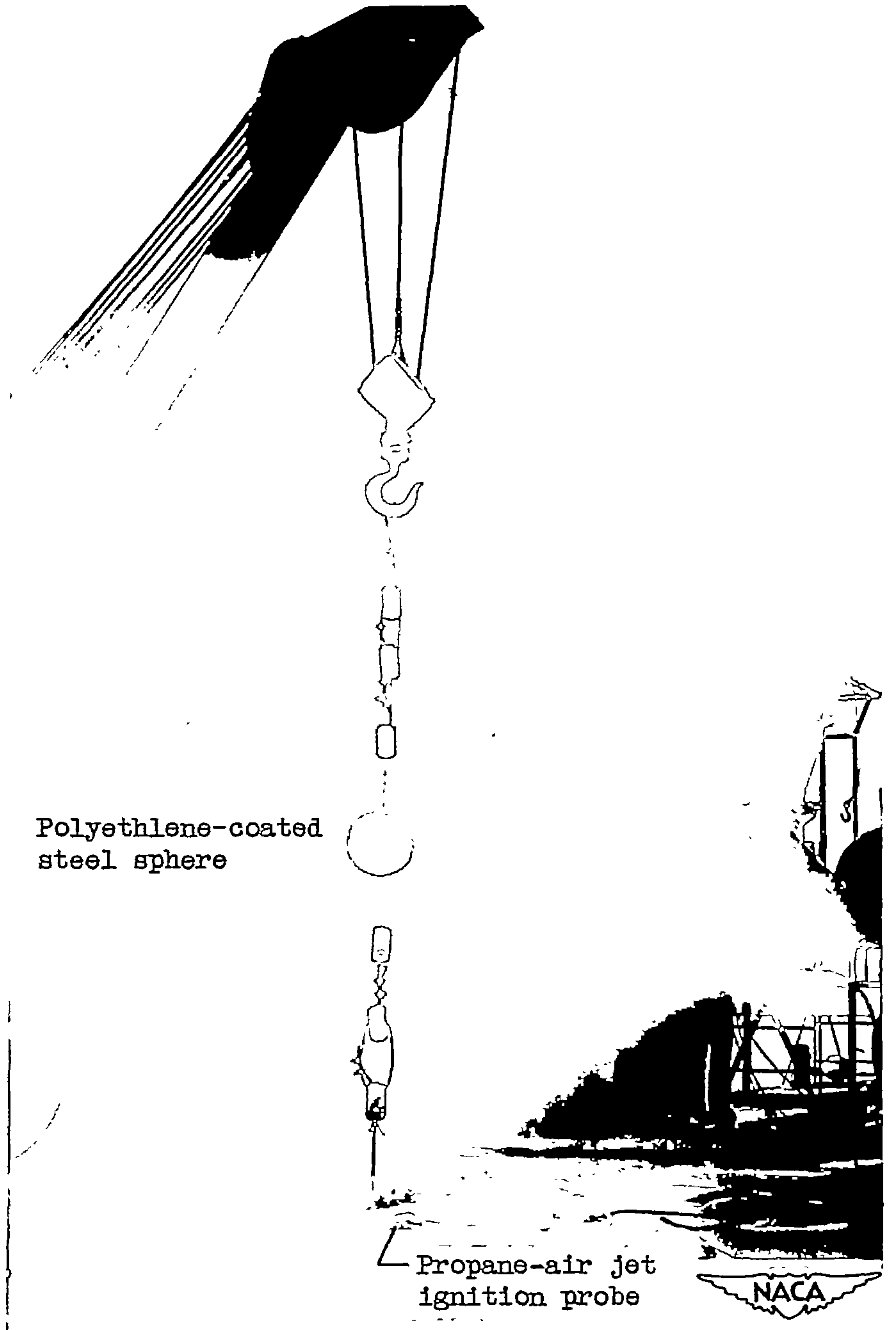

Figure 9. - Electrification of polyethylene-coated $12\frac{1}{2}$-inch-diameter steel sphere to 20 kilovolts by blowing dust and fuel mist. Air stream was diverted before making ignition capability test with propane-air jet grounded ignition probe (fig. 5).